Quantifying the vulnerability of high voltage power transmission systems to volcanic ashfall hazards

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ABSTRACT: Insulator flashover initiated by volcanic ashfall contamination compromises the reliability of high voltage transmission systems. Research at the University of Canterbury has identified the properties of volcanic ash most significant in causing the electrical breakdown of insulators due to 'flashover.' This paper describes our current quantitative research programme. The research includes development of a new testing methodology to characterise the electrical resistance of volcanic ash samples of varying composition, grain size, soluble salt content, compaction and moisture content have been analysed to better understand the properties influencing the conductivity of volcanic ash. This has allowed the creation of a physically, chemically and electrically equivalent ash proxy to be used for current and future laboratory experimentation. Results to date indicate that the electrical reistance of volcanic ash decreases with increasing soluble salt content, water content, compaction and grain size. Early contamination testing has demonstrated the adverse affects of wet volcanic ash on energised insulator strings.

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1 INTRODUCTION

High voltage electrical transmission networks are vulnerable to disruption from volcanic ashfall because of insulator flashover. Due to the vast distribution of ashfall, this may occur tens to hundreds of kilometres away from the erupting volcano. While ample anecdotal accounts exists (Fig. 1; Johnston, 1997; Tuck *et al.* 1992; Naranjo and Stern, 1998; Wilson et al. 2009), little, if any, empirical research has been undertaken to identify which characteristics of volcanic ash are most likely to induce insulator flashover. This paper identifies past impacts to electricity distribution systems and describes our current quantitative research programme. The research includes an electrical characterization of freshly erupted volcanic ash, together with the creation of a physically, chemically and electrically equivalent ash proxy to be used for current and future laboratory experimentation.

1.1 Previous known impacts

Volcanic ashfalls can cause disruption to electricity supplies in the following ways (after Wilson et al. 2009):

- Ashfall build-up on insulators can lead to flashover (the unintended electric discharge over or around the insulator), causing disruption to distribution networks.
- Line breakages and damage to towers and poles due to ash loading, both directly onto the structures and by causing treefall onto lines, particularly in heavy, fine ashfall events. Snow and ice accumulation on lines and overhanging vegetation will further exacerbate the risk.
- Breakdown of substation and control equipment such as air conditioning/cooling systems due to ash penetration which can block air intakes and cause corrosion.
- Controlled outages during cleaning.

Of these, the main hazard is insulator flashover on electricity transmission networks and substations. Factors contributing to risk of flashover include:

- Light wet weather conditions (dew, fog, drizzle or light rain) wets the ash and leads to a conductive layer forming on the surface which initiates leakage current and leads to dry-band arcing and ultimately flashover.
- Heavier rain will wash off contaminants.
- Ash grainsize (fine ash adheres to insulators more strongly).
- Insulator design and construction (ability to shed ash and resist acidic corrosion).

1.2 Insulator flashover

Insulator flashover has been studied extensively in the electrical engineering field (e.g. Jolly, 1972: Watson *et al.*, 1993; Grigsby, 2007; Gencoglu & Cebeci, 2008;). Previous experiences indicate that when a dry insulator string is uniformly coated in fine-grained volcanic ash, it is non-conducting and there will be no sizeable leakage current (measured in microamps) over the insulators' surfaces. However, as moisture gathers on the insulators' surfaces, the soluble component of the ash dissolves, forming a conducting solution through which a leakage current flows (see Wilson *et. al.,* 2009 for more information).

Insulator flashover occurs when the leakage current steadily builds up and, in time, will generate enough heat in the ash layer to induce a rate of evaporation greater than the rate of moisture accumulation. Prolonged evaporation leads to the formation of 'dry zones.' These dry zones offer a much larger resistance than the remaining conducting solution, so the entire applied voltage falls and becomes non uniform along the insulator string. Flashover occurs when the dry zone reaches a width (called critical flashover width) beyond which discharges crossing the dry zone can evaporate paths through the remaining conducting solution to reach the outer electrode (Fig 1). With further moisture, the dry zone will become wet again, allowing discharging to reoccur until the critical width has again been reached. This process will continue until the moisture stops or the ash is washed off the insulator.

Figure 1. Flashover on 33kV glass insulator strings in the University of Canterbury's high voltage laboratory. The left image illustrates flashover on a clean insulator string and the right image shows flashover on an insulator string coated with 2mm of fine grained (105μm) basaltic ash.

For a contaminated insulator operating at an AC applied voltage the discharge across the dry zone is broken every half cycle. However, as the voltage magnitude increases again, the voltage gradient across the dry zone is usually sufficient to ensure re-ignition of the discharge. Because DC arcs are never extinguished by the applied voltage passing through zero voltage, they can grow almost continuously for several seconds, enabling them to bridge greater distances over the insulator's surface.

1.3 Important chracteristics of volcanic ash

During most explosive eruptions volatiles adhere to fine ash particles (Witham et al. 2005). Sulphur and halogen gases and associated cations are adsorbed onto ash surfaces and dry to become soluble salts. When dry, volcanic ash is non-conductive due to the crystalline-solid structure of the salts which act more as an insulator than a conductor (Sarkinen and Wiitala, 1981; Johnston, 1997; Narajo and Stern, 1998; Bebbington *et. al,* 2008). However, when moisture is added to the material, these salts dissolve into solution, providing an ionic pathway for the free flow of electrons.

2 PSEUDO-ASH

Fresh, newly erupted volcanic ash is required for application to insulators during laboratory testing. Fresh ash with soluble salts still attached are usually difficult to obtain because of the low frequency of volcanic eruptions and difficulties in collection and transportation of ash. Ash also loses its soluble content rapidly in the presence of moisture (such as rain or wet soil). A pseudo-ash was thus produced to create a substance which best replicates the physical, chemical and electrical properties of freshly fallen volcanic ash.

2.1 Electrical resistance testing

Previous efforts to characterize volcanic ash have largely been restricted to the ESDD (Equivalent Salt Deposit Density) method. Sarkinen and Wiitala (1981) used the ESDD approach to evaluate the severity of contamination on insulators damaged by flashover due to

being covered in ash during the 1980 Mount St. Helens eruption. This standard method, expressed in units of mg/cm^2, deduces the equivalent amount of sodium chloride (NaCl) required to yield the same conductivity as the contaminant (volcanic ash in this case). Table 2 shows the relationship between site severity description and the corresponding ESDD measurement.

Table 2. Site Severity Index for ESDD (IEEE Definitions)

Description	ESDD (mg/cm^2)
Very Light	0-0.03
Light	0.03-0.06
Moderate	0.06-0.1
Heavy	>0.1

In this study, the electrical resistance of volcanic ash samples of varying composition, grain size and soluble salt content has been analysed to better understand the properties influencing the conductivity of volcanic ash. Volcanic ash becomes conductive depending on a number of variables.

2.2 Methods

2.2.1 Creation of pseudo-ash

Both basaltic and rhyolitic rock was used in the creation of a proxy for testing purposes. Coarse-grained bulk samples were crushed and milled using a hydraulic press and a ring pulveriser respectively. Once the rock had been pulverised to a workable grain size the material was then dry sieved to separate out five distinct grain size ranges. A range from coarse (1mm) to very fine (0.1mm) ash underwent size analysis using conventional sieves. Smaller grain sizes are of most interest due to their propensity of being able to travel farther distances and to be deposited over larger areas, hence a greater likelihood to be deposited on high-voltage electrical transmission equipment.

2.2.2 Ash dosing

Because of the importance of soluble salts and their role in increasing the conductivity of volcanic ash, sulphuric acid (H_2SO_4) and sodium chloride (NaCl) were added to a pseudo-ash to replicate the volatiles found on fresh ash. These were chosen because of their high abundance during explosive volcanic eruptions (Witham et al. 2005).

Initial concentrations were prepared on a percent by weight basis. Molar concentrations were then calculated to ensure similar ionic strengths between the sulphuric acid and sodium chloride compounds. A range of concentrations were used, as it was unclear how much would be absorbed by the ash, react with the ash surface or evaporate in the drying process.

Approximately 15mL of dry ash was placed in a 30mL plastic vial. Once solutions had been prepared to their respective molar concentrations, 5mL was added to each vial and subsequently stirred to ensure even distribution of the solution throughout the ash. Vials were then placed in an oven at ~85ºC for a period of two days. After one day of drying a hard impenetrable surface layer developed on the ash. To continue the drying process it was necessary to gently break up and mix this crust to allow underlying moisture to evaporate.

2.2.3 Electrical resistance testing procedure

Two electrical instruments were used to measure the resistance of the ash samples (in units of megohms). A high voltage 'megger' was used to take dry resistance measurements, due to the extremely high resistances. A low voltage RCL bridge was used to collect more precise data once resistance readings fell below 10,000 ohms. A special resistance-measuring device

consisting of vials housed between two electrodes was used for resistance tests. These vials were fabricated specially for these experiments as they provided an adequate space to contain both ash and water without losing any material (Fig. 2). An electric charge is emitted from the measuring apparatus and the resistance created in the circuit by the volcanic ash is calculated in ohms.

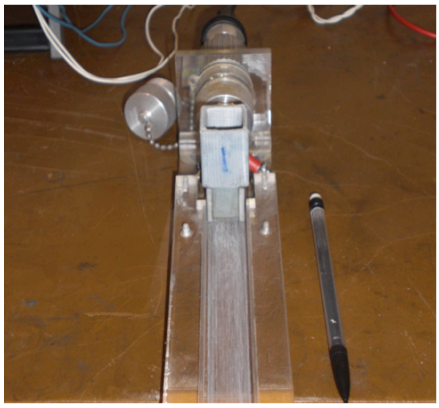

Figure 2. Ash testing vial placed in its 'electrode dock' ready to be electrically tested.

2.2.4 Addition of water

Due to the importance of maintaining a constant ionic content on ash samples, de-ionised water was used to treat the samples as well as to clean vials and tools after use. The major difficulty experienced while adding water to each ash sample was to ensure a homogenous mixture. Mixing was carried out using a metal stirring needle while de-ionised water was incrementally added on three different occasions using a 5mL pipette. Mass readings were taken for 1) the initial dry mass, 2) mass after adding initial moisture, 3) mass after stirring to account for ash lost by means of adherence to the stirring needle, 4) mass after second water addition, 5) mass after stirring, 6) mass after third water addition. These values were necessary for the calculation of density and moisture content used later in the resistance testing analysis.

2.2.5 Density/compaction test

Volcanic ash compacts naturally in the environment by up to 50% due to gravitational settling, wetting and drying processes and rainbeat compaction. In light of this, it was important to replicate a compaction scenario to adequately test electrical resistance values for volcanic ash compacted to a higher density. Firstly the ash was placed into the testing vials without any anthropogenic compaction and resistance measured. Then, a 4.5kg (10lbs) weight was arbitrarily placed on top of a compaction tool to compress the ash. Electrical resistance readings were taken for the compacted samples and compared to uncompacted values .

2.3 Results & observations

2.3.1 Moisture content

It was observed that as moisture content increases resistance decreases. Figure 3a show the results from electrical resistance testing of a basaltic and rhyolitic pseudo-ash dosed in both sodium chloride (NaCl) and sulphuric acid (H_2SO_4). Each graph illustrates the incremental decrease in resistance with each addition of moisture regardless of ash composition or ionic content. Results from these graphs suggest that tests performed with samples dosed with sodium chloride (NaCl) generally yielded lower resistance values. This may be attributed to the superior ability of sodium chloride to adhere to small-grained particles. The sulphuric acidic was also found to corrode the ash particles, in particular the rhyolitic pseudo-ash, and form a clay (mordenite) cement. As a result sodium chloride is considered the more stable compound for such applications.

2.3.2 Real ash comparison

Figure 3b illustrates the likeness between various pseudo-ash and two real ash samples (Ruapehu 1996 and Merapi 2006). In the case of a rhyolitic proxy dosed with sulphuric acid (H_2SO_4), the pseudo-ash most analogous is dosed with between 0.018M and 0.18M H_2SO_4. This comparable pseudo-ash will be replicated for use in ongoing and future experiments. However,

it must be considered that fresh ash samples from Merapi (2006) and Ruapehu (1996) may have lost some of their soluble salt content during collection, transportation and storage.

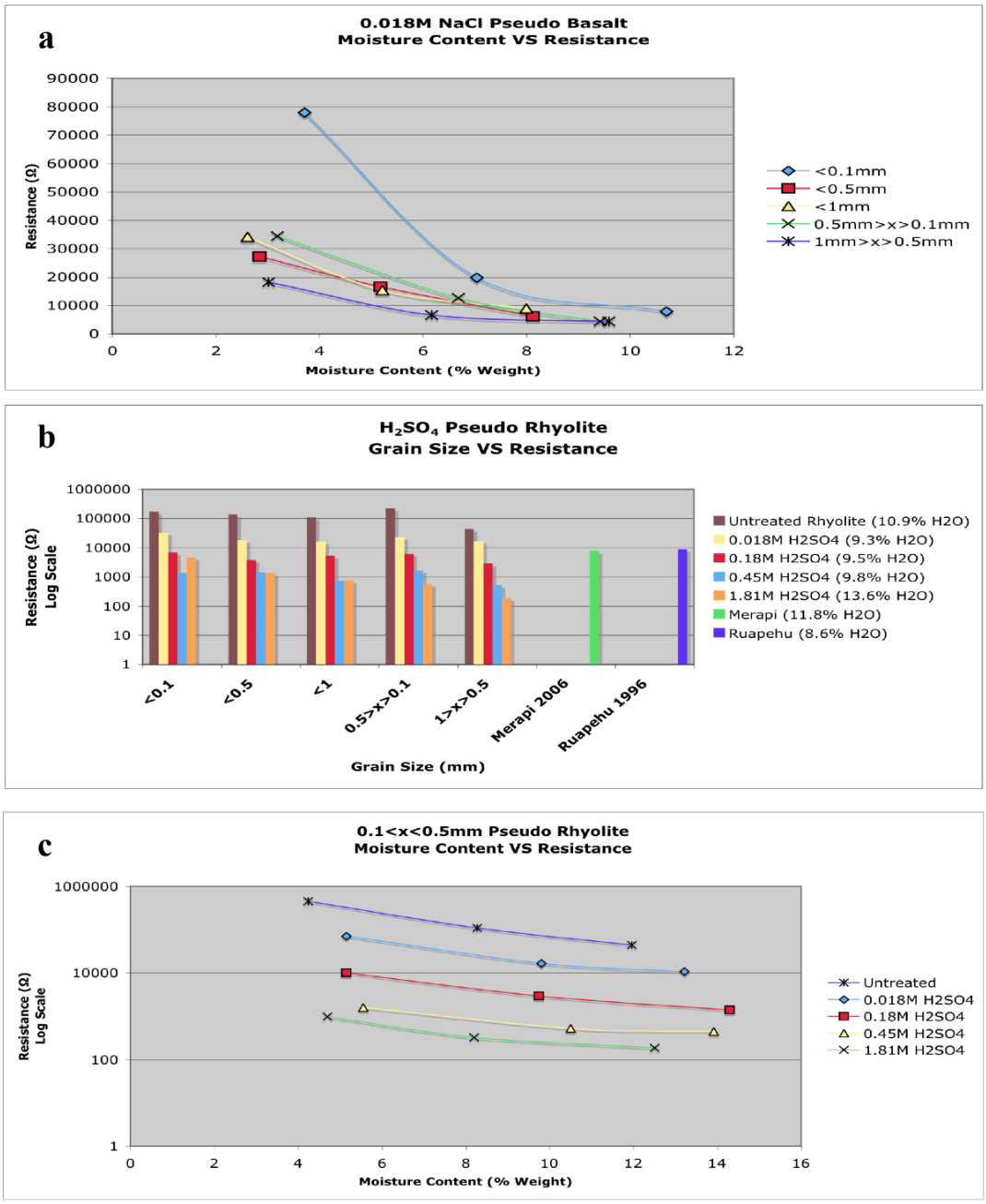

Figure 3. a) Resistance values for different grain sizes of a pseudo basalt dosed with 0.018M NaCl solution. **b)** Bar graph representing a rhyolite pseudo-ash of varying molar concentration and grain size compared with real ash samples. Numbers in brackets correspond to average moisture content values for the corresponding dosing bracket. **c)** Resistance vs moisture content for rhyolitic pseudo-ash grains 0.1<x<0.5mm dosed in varying concentrations of H_2SO_4.

2.3.3 Grain size

Results obtained from grain size measurements suggest that larger grain sizes have a lower resistance value. Figures 3a and 3b show the trend of incremental decrease in electrical resistance with increasing grain size. These figures illustrate that a pseudo-ash of grain size larger than 0.5mm but smaller than 1mm were commonly the most conductive. This may be due to the greater ability of larger grains to compact due to their larger mass and perhaps the larger void between grains allows for greater penetration of water into the mixture.

Lasersizer analyses for fresh ash samples are shown in figure 4. Mean grain size for Merapi (2006) ash was 35µm while the Ruapehu (1996) ash mean grain size was 462µm. Results indicate that it is acceptable to consider a <500µm pseudo ash as a suitable substitute for a real and fresh ash such as the one collected at Merapi (<440µm) in 2006. Similarly, the Ruapehu 1996 ash grains are comparable to a coarser-grained replication (e.g. 500µm-1mm).

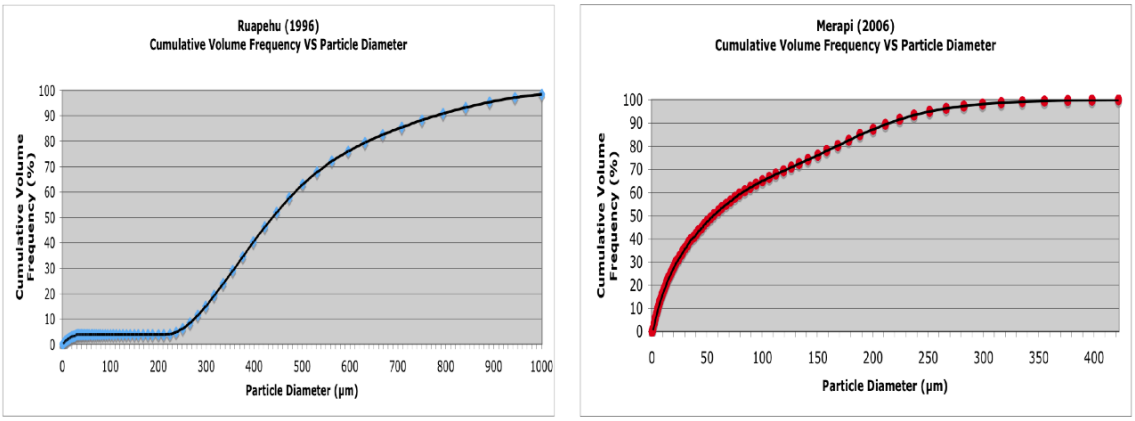

Figure 4. Grain size distributions for fresh ash collected from Ruapehu (1996) and Merapi (2006) respectively.

2.3.4 Ionic concentration

Figures 3a, 3b, and 3c show different grain sizes of either basaltic or rhyolitic pseudo-ash dosed with several concentrations of either sodium chloride (NaCl) or hydrochloric acid (H_2SO_4). Trends suggest that with each increase in molar concentration of either solution, resistance values decrease and the pseudo-ash types gradually become more conductive in nature. In general, the more soluble salt content adhered to volcanic ash grains the higher its conductivity will become.

Electrical resistance data for especially high doses of H_2SO_4 applied to rhyolite samples were not achieved due to the compound's inability to dry. Because the pseudo-ash would not dry, incremental moisture calculations could not be recorded. Though both sources of soluble salts (NaCl and H_2SO_4) generated the same result of decreasing resistance with increasing ionic content it was decided that future requirements for a pseudo-ash would utilize sodium chloride as a dosing agent as it is safer to work with and does not compromise the chemical integrity of the ash mineralogy.

2.3.5 Density/compaction

Figure 4 shows that compaction rates in freshly fallen ash will play a big role in the conductivity of the material. Compaction tests show that the denser the (wet) material is the more conductive it becomes. An increase in compaction or density of the material means an increased number of contact points between grains which thereby facilitates the flow of electricity. In the case of compacted ash layers, smaller grains will prevail as the most conductive material due their larger surface area and therefore fewer voids and more contact points between grains.

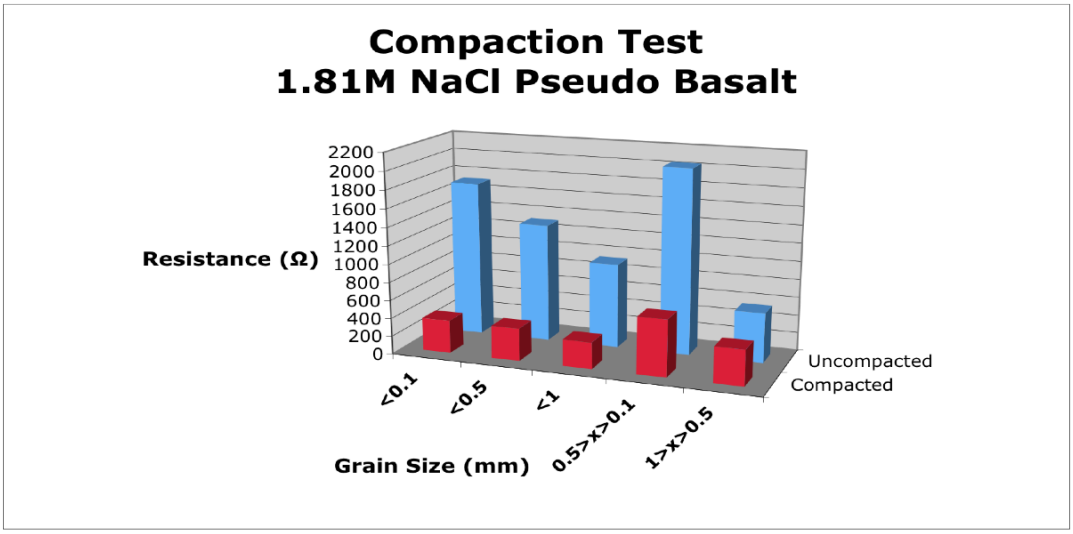

Figure 5. Compaction data illustrating the decrease in resistance with an increase in compaction.

3 PRELIMINARY RESULTS OF CONTAMINATION TESTS

3.1. Dry tests

Table 3 shows the flashover voltages for high voltage insulators in a clean, uncontaminated state compared with those for insulators coated in 1-4mm of dry, fine grained (<105µm) 0.018M NaCl basalt. This early data suggests that dry volcanic ash is non-conductive, will not initiate any significant leakage current and will not produce a flashover without some source of moisture. Variations in flashover voltage may be attributed to atmospheric differences that cause slight variations in flashover potential.

Table 3. Flashover voltages for insulators in a clean state compared with those for insulators coated in 1-4mm of fine grained (<105µm) pseudo basalt.

	# Sheds	Clean State	1-4mm DRY Ash
PORCELAIN	1	88.8kV	85.2kV
	2	172.3kV	167.4kV
	3	226.1kV	241.6kV
	4	280.4kV	290.4kV
	5	345.5kV	371.6kV

It was noted while running dry contamination tests was the wind created by corona activity leading up to flashover. As the voltage increased, the number of electrons emitted from the ionization of the surrounding air were significant enough to create a convection that removed 2-4mm of fine grained (105µm) 0.018M NaCl basalt in a static-wind environment (Fig 6).

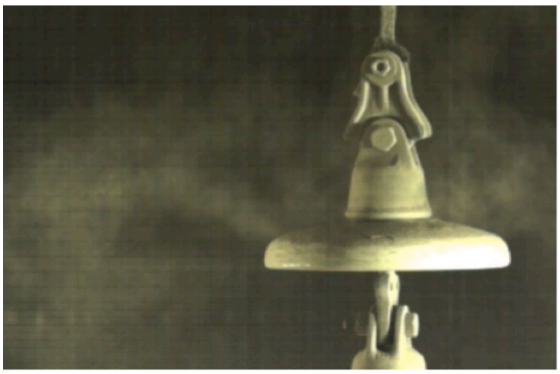

Figure 6. High-speed image of 'corona wind' shedding 1-2mm of dry basaltic ash deposited on a porcelain insulator in a static wind environment. The corona wind was strong enough to naturally discard 40% of the dry ash from the insulator's surface.

3.2 Wet tests

During a preliminary exercise a 33kV insulator string was coated with 2mm of fine grained (105µm) 0.18M NaCl basalt and then wetted with a hand sprayer to replicate a moist environment. Under this polluted condition the flashover voltage was recorded at 70kV. Flashover voltage recorded on the same string of insulators in a clean state was 226kV. The drastic reduction in voltage required to produce a flashover on a polluted insulator string in a moist environment is nearly four hundred percent lower than that required for a clean string.
Future work will strive to quantify the geological, environmental, atmospherical and electrical parameters most responsible for initiating flashover on high voltage transmission insulators. Additionally, leachate analyses of both fresh and manufactured ash will be carried out to further compare their ionic properties. Future directions for contamination testing include but are not limited to extensive fog chamber testing, testing insulators of different ratings and compostions, direct current (dc) testing of contaminated insulators, room temperature vulcanizing (RTV) grease applications and resistivity testing for substation gravel contaminated with volcanic ash.

4 CONCLUSIONS

High voltage electrical transmission networks are vulnerable to disruption from volcanic ashfall hazards. Our research programme will investigate the identified knowledge gaps surrounding ash-induced flashover on high voltage transmission systems. In particular, we are aiming to identify the parameters most influential in causing flashover. Recognizing the variables which threaten the integrity of power transmission systems during a volcanic eruption is a prudent part of succesful risk management. The following conclusions can be drawn from the work to date:

- Existing literature conveys the vulnerability of high voltage transmission networks to volcanic ashfall hazards. Much work remains to accurately quantify the variables leading up to and resulting in flashover on high voltage insulators contaminated with volcanic ash.
- Dry volcanic ash is non conductive until water moisture can dissolve attached soluble salts, thereby dramatically increasing electrical conductivity.
- The greater the volume of soluble ions on the ash, the greater the ash's conductivity.
- The denser the layer of ash upon deposition, the more conductive the material will be.
- Larger ash grainsizes appear to be more conductive than finer grainsizes, suggesting that larger grains play a larger role in the initiation of flashover than previously perceived.
- Moist volcanic ash greatly reduces the flashover voltage on porcelain insulator strings.

- An ash proxy can be created to sufficiently replicate the electrical and geological properties of a fresh ash sample for use in laboratory testing.

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